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## **A modular entrainment model for cohesive sediment**

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### **KEY WORDS**

Cohesive sediment, entrainment, bioturbation, consolidation, models

This paper describes an entrainment model for cohesive sediments that is based on a power-law expression for the excess shear stress and a total entrainment coefficient. Total entrainment includes terms for consolidation, bioturbation, and all other processes (base entrainment coefficient). The model is used to predict entrainment rates for cohesive sediments from Lake Erie, the Tamar Estuary, Long Island Sound, and the Fox River, Wisconsin. The base entrainment coefficient, which is estimated using samples with the least post-depositional modification, is unique for each sediment suite because it includes environmentally sensitive processes like mineralogy, salinity, organic carbon content, etc. Based on available entrainment measurements, expressions are presented for the consolidation and bioturbation coefficients. The model is evaluated with entrainment data for identical sediment that has been either consolidated or bioturbated and the comparison is encouraging. A comparison of predicted and measured entrainment rates for undisturbed sediment is less favorable because of its unknown post-depositional history.

### **1. INTRODUCTION**

Cohesive sediments are of interest because of their role in shoaling processes in estuaries and harbors, contaminant transport, and marine structural design. The primary motivation of the U.S. Navy, however, is their impact on the physical and acoustic properties of the seabed and on the optical properties of the water column. The physical



and chemical environment determines the dynamics of cohesive sediment but interactions between processes within the seafloor and the water column are poorly known. This problem is solved through a dependence on field and laboratory measurements in non-military applications, but this approach is generally unavailable for military operations. Thus, more general methods need to be developed. This paper discusses one such approach that relies less on direct observations of cohesive sediment behavior.

## 2. BACKGROUND

A substantial research effort has gone into understanding erosion (also called entrainment or resuspension), deposition, and consolidation (*e.g.*, Partheniades, 1993; Toorman, 1996) of cohesive sediments. The entrainment of fine grained sediment is usually parameterized using a power-law function that incorporates the bottom shear stress. For example, Ariathurai *et al.* (1983) proposed the following expression for the entrainment rate,  $E$ :

$$E = M \left( \frac{\tau_b - \tau_c}{\tau_c} \right) \quad (\text{kg/m}^2/\text{s}) \quad (1)$$

where:  $M$  = the rate constant ( $\text{kg/m}^2/\text{s}$ ) at  $\tau_b = 2\tau_c$ ;  $\tau_b$  = bottom stress; and  $\tau_c$  = critical shear stress for entrainment, which has been found to increase with depth for undisturbed sediment (*e.g.*, Sanford and Maa, 2001). Note that in this paper, we will use a constant value of 0.04 Pa for  $\tau_c$  when it is not available. Partheniades (1965) suggested that erosion rates for mud (60% clay), while being constant for some experimental conditions, could only be described by a complex function with a large number of coefficients. Parchure and Mehta (1985) found that the erosion rate of deposited beds was not constant in part because of consolidation and dewatering. They turned to the theory of chemical rate processes to explain the dynamics of cohesive sediments, thereby implicitly making entrainment dependent on inter-particle bonds and thus the bio-geochemical environment. The parameters in their proposed formulation were determined by fitting experimental data. Lavelle *et al.* (1984) examined the data from a number of studies and proposed the following expression for the erosion rate:

$$E = \alpha |\tau_b|^\eta \quad (\text{kg/m}^2/\text{s}) \quad (2)$$

where the parameters  $\alpha$  and  $\eta$  were determined by least-squares fit to the data from each set of experiments. The parameter  $\alpha$  varies by three orders of magnitude. More recently, Lick *et al.* (1995) proposed the following expression for the resuspension potential for cohesive sediments:

$$\varepsilon = \frac{\alpha}{t_d^n} [\tau_b - \tau_c]^m \quad (\text{kg/m}^2) \quad (3)$$

where  $\alpha$ ,  $n$ , and  $m$  are constants, and  $t_d$  is the time after deposition in days. If the shear stress is held constant, the entrainment rate can be found from  $\varepsilon/T$ , where  $T$  is the time interval over which the entrainment remains constant (equilibrium time step). Experimental work has indicated that the mean concentration of entrained sediment in laboratory flumes reaches a steady state in approximately 1 hr (Lick, 1982). The entrainment rate can be deduced from the initial slope of the concentration time series, implying that  $E$  will go to zero when an equilibrium concentration is reached. Thus, some data are reported as a mean entrainment rate (or first-hour rate) for this equilibrium interval (see Lick, 1982). For these data, we calculate  $E$  from  $\varepsilon$  using  $T = 3600$  s. Note that only Eq. 1 is dimensionally correct. This brief summary is intended to show that there is no unifying theory of the physical processes that control the entrainment of cohesive sediments and that most entrainment models use empirical parameters that are derived from observations of sediments from the area of interest.

The influence of biological and physical processes on the erosion of mudflats has been examined in the INTRMUD project (Black *et al.*, 1998), which demonstrated the importance of biostabilization on entrainment (de Brouwer *et al.*, 2000; Droppo *et al.*, 2001). The LISP project (Littoral Investigation of Sediment Properties) (Daborn, 1991) also examined the complex interaction of microflora and fauna in the intertidal environment. The biostabilization effect of biofilms is opposed by the destabilization caused by bioturbation (Grant and Daborn, 1994; Green *et al.*, 2002). Laboratory work with natural sediments has shown that cohesive sediment erodibility increases rapidly with the activity of infauna, presumably because of their destruction of inter-particle bonds and primary depositional fabric (Tsai and Lick, 1988; Lintern *et al.*, 2002). The complex interaction of these biological processes with physical processes like hydrodynamics and consolidation necessitates the use of more realistic entrainment models, and carefully planned measurement programs (Tolhurst *et al.*, 2000; Lick *et al.*, 1998).

### 3. METHODS

The purpose of this study is to evaluate sediment entrainment using a modular approach, which isolates the inherent physical properties of sediment from consolidation and bioturbation effects. The proposed model is first presented and the method of determining expressions for the coefficients for bioturbation  $A_B$  and consolidation  $A_C$  is then discussed.

#### 3.1. The entrainment model

The entrainment expressions discussed in the literature are predominantly derived by fitting a power-law function to a series of data points on a plot of  $\tau_b$  versus  $E$ . The power varies by many orders of magnitude, depending on the shear stress function. For example, powers as low as  $10^{-8}$  were used by Lavelle *et al.* (1984) in Eq. 2, whereas a power of 1 is implied by a linear model (Eq. 1), and the resuspension potential (Eq. 3) uses a coefficient greater than 1. These expressions all have leading coefficients that are either constant or variable. This simple function fits a range of data because the sediment concentrations of interest to most problems are small, which is the appropriate application of a power-law function. This function is inappropriate for fluid mud, however, and more complex models are required (*e.g.*, Kranenburg and Winterwerp, 1997).

The model we propose to describe cohesive sediment entrainment is also based on a power-law expression, but physical and biological processes are isolated so that they can be evaluated separately. This is done conceptually by decomposing the leading constant into independent coefficients:

$$E = A_B A_C A_0 \left( \frac{\tau_b}{\tau_c} - 1 \right)^m \quad (4)$$

where  $A_B$ ,  $A_C$ , and  $A_0$  are parameters to be determined from observations. This formulation is similar to Eq. 1 but the excess shear stress power  $m$  can vary from unity. The parameter  $A_0$  is analogous to the leading coefficients used in other expressions. It is treated as a fundamental entrainment rate for specific sediment, which has undergone no post-depositional modification (*i.e.*, no consolidation or bioturbation). The parameters  $A_B$  and  $A_C$  represent biological reworking and consolidation processes, respectively; if no consolidation or bioturbation has occurred, both  $A_B$  and  $A_C$  will equal 1, indicating no effects. We neglect biostabilization (*i.e.*, biofilms). Thus, our model incorporates a



fundamental entrainment rate that is a function of excess shear stress, and which is modified by post-depositional consolidation and bioturbation. The values of the parameters will be discussed in the results section.

This study focuses on sediment entrainment and, therefore, suspended sediment profiles will not be calculated or discussed. Equation 4 will be evaluated using entrainment rates derived from annular flumes (Fukuda and Lick, 1980; Tsai and Lick, 1988), the Instrument for measuring Shear stress In Situ (ISIS; Lintern *et al.*, 2002) and directly measured by SEDFLUME (McNeil *et al.*, 1996). The shear stress  $\tau_b$  can be calculated from the hydraulic flow in all of these devices and thus the critical shear stress  $\tau_c$  can be estimated. However, the definition of  $\tau_c$  is partially subjective and not all workers define it the same. For example, McNeil *et al.* (1996) define  $\tau_c$  as the shear stress that produces an erosion rate (measured by SEDFLUME) between  $10^{-5}$  and  $10^{-6}$  m/s; thus the mass erosion rate ( $\text{kg/m}^2/\text{s}$ ) is dependent on the sediment bulk density. We use measured bulk densities to calculate entrainment rates for comparison to the model and other results. Lintern *et al.* (2002), however, define  $\tau_c$  as the stress at which the entrainment rate increases from a previous steady value (see their Figure 3). The definition of the critical shear stress reported by different authors is dependent on measurement methods, and this variability will contribute to uncertainty in the results of this study.

### 3.2. Experimental procedure

The coefficients  $A_0$ ,  $A_C$  and  $A_B$  in Eq. 4 must be estimated in order to isolate the impacts of bioturbation and consolidation from other processes. Ideally, this would be accomplished using entrainment data for undisturbed sediments, but this approach cannot be used because the post-depositional history of such sediments is unknown. We will use homogeneous sediment that was deposited from slurries to find functions of  $A_C$  and  $A_B$ , whereas  $A_0$  will be independently determined for each sediment suite. The data consist of measured entrainment rates  $E$ , the resuspension potential  $\epsilon$ , and the equilibrium concentration  $C_M$  at different shear stresses, water contents, and consolidation intervals. The sediments vary somewhat and caution is necessary in developing parameterizations for general applicability. Nevertheless, this first-order calculation of the coefficients will assist in future efforts to understand these processes. For ease of comparison, all entrainment measurements will be transformed into an entrainment rate  $E$  ( $\text{kg/m}^2/\text{s}$ ), which requires approximation of unreported experimental parameters for some data.

The base entrainment parameter  $A_0$  is strongly dependent on clay mineralogy, salinity, and seabed chemistry. These variables are not considered in this study and thus they

they are implicitly included in  $A_0$ . For this reason,  $A_0$  is expected to have a unique value for each sediment suite discussed in this report. This coefficient should be determined from sediment that has undergone minimal post-depositional modification. For each suite of data (e.g., Lake Erie sediment from Table 1), samples that are assumed to be the least modified by post-depositional processes are used to fit Eq. 4 and thus find a value of  $A_0$ . This approach assumes that  $A_B = A_C = 1$ , which is reasonable for newly deposited sediment. This procedure is repeated for each data set and unique values of  $A_0$  are found.

Fukuda and Lick (1980) report entrainment results for mud (67.7% clay) from the central part of Lake Erie (Table 1). Sediment samples were allowed to consolidate from slurries for periods of 1 to 10 days. It is assumed in this study that the sediment had not consolidated significantly within one day, which is equivalent to a water content of 74% (shaded rows in Table 1). This is the shortest consolidation interval for which data are available. The solution to Eq. 4 assumes there has been no bioturbation or consolidation (i.e.,  $A_B = A_C = 1$ ) and we are solving for  $A_0$  and  $m$  only. However, we will use a constant value of 3 for the parameter  $m$ , following Lick *et al.* (1994). Fukuda and Lick (1980) do not report a value for  $\tau_c$  so we use a value of 0.04 Pa, which is reasonable for recently deposited mud. Equation 4 is fit to the available high-water-content data with only  $A_0$  as an adjustable parameter.

Table 1. Experimental conditions and entrainment rates (kg/m/s) for Lake Erie sediment (Fukuda and Lick, 1980).  $E_0$  = measured;  $E_{M1}$  = calculated by Eq. 4 with  $A_C$  (initial) =  $A_B = 1$ ,  $A_0 = 3.61 \times 10^{-4}$  kg/m<sup>2</sup>/s,  $m = 3$ , and  $\tau_c = 0.04$  Pa.

$\tau_b$ (Pa)	Water Content (%)	Measured $E_0$	Predicted $E_{M1}$	$E_0/E_{M1}$ (Estimated $A_C$ )
0.0875	74.0	$8.04 \times 10^{-4}$	$6.04 \times 10^{-4}$	1.3300
0.0636	74.0	$5.94 \times 10^{-5}$	$7.41 \times 10^{-4}$	0.8012
0.0947	69.5	$1.08 \times 10^{-4}$	$9.23 \times 10^{-4}$	0.1170
0.0677	69.5	$1.18 \times 10^{-5}$	$1.12 \times 10^{-4}$	0.0984
0.1091	64.0	$1.02 \times 10^{-4}$	$1.86 \times 10^{-3}$	0.0548
0.0885	64.0	$4.79 \times 10^{-6}$	$6.43 \times 10^{-4}$	0.0074
0.1133	61.5	$1.77 \times 10^{-5}$	$2.22 \times 10^{-3}$	0.0079
0.0915	61.5	$3.70 \times 10^{-6}$	$7.70 \times 10^{-4}$	0.0048
0.0616	61.5	$3.53 \times 10^{-7}$	$5.68 \times 10^{-5}$	0.0062

The consolidation coefficient  $A_C$  for all sediment suites is evaluated using laboratory entrainment data for the Lake Erie sediment, which contained no organisms. The value of  $A_0$  determined for the high-water-content data is used to calculate entrainment rates for the experiments at longer consolidation intervals, which correspond to lower water contents (Table 1). The ratio of the measured ( $E_0$ ) and modeled ( $E_{M1}$ ) entrainment rates is the estimated consolidation coefficient  $A_C = E_0/E_{M1}$ , which is plotted against the water content in Fig. 1. A function for  $A_C$  is derived from these points. Note that the selected function is strongly dependent on the larger values of  $A_C$  at high water contents. The result of this data-fitting procedure will be discussed in the results section.

An analogous procedure is used to estimate the bioturbation parameter  $A_B$ . We will use entrainment data for homogeneous slurries produced from Tamar Estuary sediments with infauna (Lintern *et al.*, 2002). These samples had consolidation intervals of 5 to 58 days (Table 2) and exhibited obvious biological effects. Although these sediments exhibited an increase in density with time, they will be treated in this study as having been dominated by bioturbation (*i.e.*,  $A_C = 1$ ) as observed in the entrainment data, which will be discussed in the results section. To determine a baseline coefficient  $A_0$  for these sediments, we again use samples with the shortest time since deposition, which for these sediments is 5 days (shaded rows in Table 2), and apply Eq. 4. Ideally, the value of  $A_0$  can be determined for a specific sediment type but, since the mineralogy of the Tamar

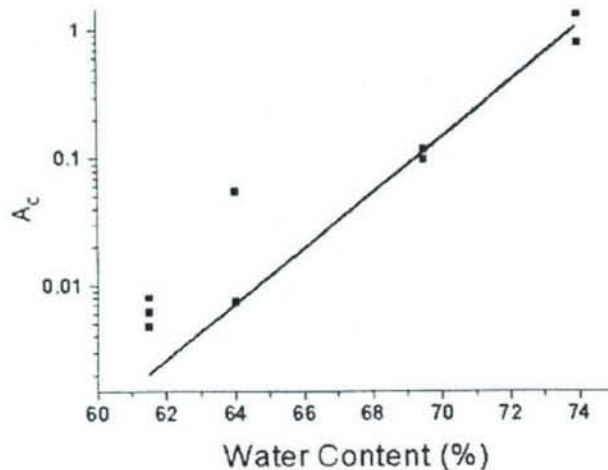


Fig. 1. Plot of the consolidation parameter  $A_C$  for the data from Table 1. The line is a plot of Eq. 5 ( $r^2 = 0.4597$ ). Note that  $A_C \equiv E_0/E_{M1}$  from Table 1.



Table 2. Experimental conditions and entrainment rates ( $\text{kg/m}^2/\text{s}$ ) for ISIS experiments (Lintern *et al.*, 2002).  $E_0$  = measured;  $E_{M1}$  = calculated by Eq. 4 with  $A_B$  (initial) =  $A_C = 1$ ,  $A_0 = 1.79 \times 10^{-5} \text{ kg/m}^2/\text{s}$ , and  $m = 3$ .

$\tau_b$ (Pa)	$\tau_c$ (Pa)	Consolidation Interval (days)	Measured $E_0$	Predicted $E_{M1}$	$E_0/E_{M1}$ (Estimated $A_B$ )
0.2	0.100	5	$1.97 \times 10^{-5}$	$3.92 \times 10^{-8}$	$5.02 \times 10^2$
0.5	0.100	5	$5.44 \times 10^{-5}$	$1.09 \times 10^{-4}$	$5.0 \times 10^{-1}$
0.1	0.010	19	$2.97 \times 10^{-5}$	$1.30 \times 10^{-2}$	$2.28 \times 10^{-3}$
0.2	0.010	19	$4.94 \times 10^{-5}$	$1.23 \times 10^{-1}$	$4.03 \times 10^{-3}$
0.5	0.010	19	$1.43 \times 10^{-4}$	2.11	$6.82 \times 10^{-5}$
0.1	0.075	30	$2.11 \times 10^{-5}$	$6.63 \times 10^{-7}$	$3.18 \times 10^1$
0.2	0.075	30	$5.19 \times 10^{-5}$	$8.29 \times 10^{-5}$	$6.27 \times 10^{-1}$
0.1	0.065	43	$2.97 \times 10^{-5}$	$2.79 \times 10^{-6}$	$1.06 \times 10^1$
0.2	0.065	43	$9.92 \times 10^{-5}$	$1.60 \times 10^{-4}$	$6.18 \times 10^{-1}$
0.1	0.073	58	$5.44 \times 10^{-5}$	$9.06 \times 10^{-7}$	$6.01 \times 10^1$
0.2	0.073	58	$7.55 \times 10^{-5}$	$9.42 \times 10^{-5}$	$8.02 \times 10^{-1}$

Estuary mud is different from that of Lake Erie mud, it is not expected that  $A_0$  will be the same. The effect of mineralogy is beyond the scope of this work. The erosion data from Lintern *et al.* (2002) are reported as total entrainment  $\epsilon$ , which is an equilibrium value ( $\text{kg/m}^2$ ). This is transformed into the entrainment rate  $E_0$  by dividing by an estimated time step of 3600 s, based on the results of Fukuda and Lick (1980). This permits a quantitative comparison of the solutions of Eq. 4 for the data contained in Tables 1 and 2.

The consolidation and bioturbation functions that are derived for  $A_C$  and  $A_B$ , respectively, will be evaluated using mud from Long Island Sound (Tsai and Lick, 1988) and undisturbed cores from the Fox River in Wisconsin (McNeil *et al.*, 1996). The Long Island mud was processed to be completely sterile. Some samples were subsequently seeded with *Nucula*, thus supplying an opportunity to examine the relative effects of consolidation and bioturbation on the same sediment. The Fox River data is included as a demonstration of the many problems that are encountered with cohesive sediments because of the unknown depositional history, overall coarse grain size, and high organic carbon content of this sediment.

#### 4. RESULTS AND DISCUSSION

This section will use the laboratory entrainment data described above to determine expressions for the coefficients in Eq. 4. In all of the work discussed below, the value of  $m$  is equal to 3. Where unavailable from the source, an erosion time step of 3600 s will be assumed. The value of  $\tau_c$  will be taken from the sources where given, or set to 0.04 Pa where unknown. We are unaware of experiments designed to address this specific problem so we will use available data with the understanding that they may not be well-suited for our purposes.

##### 4.1. Base entrainment coefficient, $A_0$

The entrainment data with the largest water content from the Lake Erie samples (shaded rows in Table 1) are used to find a best-fit of Eq. 4 and thus the value of  $A_0$  for this suite of data. The resultant base entrainment of  $3.61 \times 10^{-4}$  kg/m<sup>2</sup>/s is used in the next section to determine the appropriate function for  $A_c$ . Similarly, Eq. 4 is fit to the Tamar mud with the shortest consolidation time and presumably least bioturbation (shaded rows in Table 2), and a value of  $1.79 \times 10^{-5}$  kg/m<sup>2</sup>/s is estimated for  $A_0$ . The functional form of  $A_B$  will be found below using this value in Eq. 4 for the data in Table 2, as discussed in the previous section.

The Long Island Sound data are shown in Table 3, and the sediments with the highest water content (shaded rows) are used to calculate  $A_0$  for this sediment. The best fit of Eq. 4 is found for  $A_0$  equal to  $1.523 \times 10^{-7}$  kg/m<sup>2</sup>/s, with  $\tau_c = 0.04$  Pa and a time step of 3600 s. The sediment cores from the Fox River (Table 4) were undisturbed. A core from a water depth of 5.9 m in Trenton Channel consists of silt and clay, with gas bubbles, and surface oligochaetes and macrophytes (McNeil *et al.*, 1996). This sediment has an unknown history of consolidation and bioturbation along with other influences that are not examined in this study. In order to determine  $A_0$  we need to evaluate the entrainment rate for newly deposited sediment, which is unlikely for these samples. Nevertheless, this exercise is instructive in demonstrating the limitations of the model. We will neglect bioturbation in this sediment because we have no information on deposition time, whereas the water content was measured. The following variables are used:  $\tau_c = 0.1$  Pa, an erosion time step of 3600 s, and  $m = 3$ . The best-fit value of  $A_0$  is  $2.295 \times 10^{-2}$  kg/m<sup>2</sup>/s.

The base entrainment rates for the freshwater sediment from Lake Erie and the Fox River are much larger than for the estuarine sediment from the Tamar Estuary and Long Island Sound. This is a result of the salinity of seawater, which increases aggregation of clay minerals (Ariathurai *et al.*, 1983). It should be possible to identify a functional form for this process as well if appropriate experimental data are available. The large-

Table 3. Experimental conditions and entrainment rates ( $\text{kg/m}^2/\text{s}$ ) for Long Island Sound sediment (Tsai and Lick, 1988).  $E_0$  is measured;  $E_{M1}$  is calculated by Eq. 4 with  $A_B = A_C = 1$ ,  $A_0 = 1.523 \times 10^{-7} \text{ kg/m}^2/\text{s}$ , and  $m = 3$ ;  $E_{M2}$  is computed the same as  $E_{M1}$  but with  $A_C$  calculated from Eq. 5.

$\tau_b$ (Pa)	Water Content (%)	Measured $E_0$ ( $\text{kg/m}^2/\text{s}$ )	Predicted $E_{M1}$ without consolidation	Predicted $E_{M2}$ with consolidation
0.1	71.3	$5.60 \times 10^{-7}$	$4.643 \times 10^{-7}$	$1.27 \times 10^{-7}$
0.2	71.3	$8.06 \times 10^{-6}$	$9.74 \times 10^{-6}$	$2.67 \times 10^{-7}$
0.4	71.3	$1.15 \times 10^{-4}$	$1.11 \times 10^{-4}$	$3.04 \times 10^{-5}$
0.1	71	$6.14 \times 10^{-7}$	$4.64 \times 10^{-7}$	$1.09 \times 10^{-7}$
0.2	71	$2.61 \times 10^{-6}$	$1.01 \times 10^{-5}$	$2.38 \times 10^{-6}$
0.4	71	$9.51 \times 10^{-6}$	$1.08 \times 10^{-4}$	$2.55 \times 10^{-5}$
0.8	71	$1.41 \times 10^{-4}$	$1.04 \times 10^{-3}$	$2.47 \times 10^{-4}$
0.2	69.9	$1.34 \times 10^{-6}$	$9.74 \times 10^{-6}$	$1.32 \times 10^{-6}$
0.4	69.9	$2.90 \times 10^{-6}$	$1.11 \times 10^{-4}$	$1.50 \times 10^{-5}$
0.8	69.9	$9.83 \times 10^{-5}$	$1.04 \times 10^{-3}$	$1.41 \times 10^{-4}$
1.2	69.9	$3.73 \times 10^{-4}$	$9.56 \times 10^{-6}$	$1.29 \times 10^{-6}$

Table 4. Entrainment rate for Fox River sediments (McNeil *et al.*, 1996). The model predictions ( $E_{M1}$ ) were calculated using  $A_0 = 2.295 \times 10^{-2} \text{ kg/m}^2/\text{s}$ ,  $A_B = 1$ ,  $A_C = \text{Eq. 5}$ ,  $\tau_c = 0.1 \text{ Pa}$ , an equilibrium time of 3600 s, and  $m = 3$ .

Depth (m)	$\tau_b$ (Pa)	Water Content (%)	Measured $E_0$ ( $\text{kg/m}^2/\text{s}$ )	Predicted $E_{M1}$ ( $\text{kg/m}^2/\text{s}$ )
0.017	0.25	64.8	7.74	$8.13 \times 10^{-4}$
0.27	0.25	50.0	$4 \times 10^{-4}$	$3.07 \times 10^{-4}$
0.26	0.6	50.0	$5.28 \times 10^{-2}$	$1.14 \times 10^{-2}$
0.34	1.1	60.0	$6.36 \times 10^{-2}$	$9.11 \times 10^{-2}$
0.15	2.2	49.0	$8.57 \times 10^{-2}$	$8.44 \times 10^{-1}$
0.22	4.5	49.0	$4.18 \times 10^{-1}$	7.76



base entrainment rate for the Fox River data further suggests that bioturbation may also be an important process at this location, as indicated by the presence of organisms at the river bed.

#### 4.2. The consolidation coefficient, $A_C$

The entrainment data for the Lake Erie sediment are used to determine an expression for  $A_C$  because they have the largest range of water content (61.5 – 74%), and presumably consolidation. The values of  $E_0/E_{M1}$  from Table 1 are an estimate of the consolidation coefficient  $A_C$ , which is plotted against water content in Fig. 1. An exponential function is fit to these data:

$$A_C = C_1 e^{(W-W_0)/t} \quad (5)$$

where:  $C_1 = 0.00397$ ,  $t = 1.99315$ ,  $W$  = water content (%), and  $W_0 = 62.85$  for this study. The squared correlation coefficient  $r^2$  for Eq. 5, as plotted in Fig. 1, is 0.4597. The range of water content for which Eq. 5 is valid is limited by the data used to derive it, which in this case is 61.5 to 74%. An exponential function is reasonable because consolidation can be represented to first-order as an exponential process. However, the constants  $C_1$ ,  $W_0$ , and  $t$  are dependent on the specific data used to find  $A_C$ , and their values will change as other data are examined as will the functional form of Eq. 5. Equation 5 implies that as sediment is compacted and  $W$  decreases, the entrainment rate will decrease as well. With respect to the model, this indicates that small values of  $A_C$  correct for the base entrainment rate over-predicting the entrainment, because of an increase in  $\tau_c$ . This error increases with consolidation. If the data used to calculate  $A_0$  are properly selected,  $A_C$  should always be less than unity but this is unlikely due to measurement uncertainties and the influence of processes not included in the model.

#### 4.3. The bioturbation coefficient, $A_B$

The laboratory data for slurries from the Tamar Estuary are used to examine the functional form of the bioturbation coefficient  $A_B$  because they are dominated by biological processes and the results are well documented. Before determining the bioturbation function, it is useful to note the difficulty in using Eq. 4 for biologically influenced sediment. The ratio  $E_0/E_{M1}$  for the low-shear-stress data used to calculate  $A_0$  (top row in Table 2) exceeds 500, which is significantly greater than any other value in the table. This occurs because the  $(\tau/\tau_c - 1)$  term in Eq. 4 is less than unity for this experiment, resulting in a substantial decrease in the predicted entrainment. This may be due to many causes that are not included in the model. This phenomenon has been noted by

Lavelle *et al.* (1984) and it is of continuing interest in predicting cohesive sediment entrainment. We will not use the error data from this experiment in deriving  $A_B$ , however, because it skews the resulting function.

The bioturbation parameter  $A_B$ , which is estimated from the ratio of  $E_0/E_{M1}$  (Table 2), is plotted as a function of consolidation time in Fig. 2. These data are represented by the following expression:

$$A_B = C_2 + C_3 t_d + C_4 t_d^2 \quad (6)$$

where:  $C_2 = 5.093 \times 10^{-3}$ ;  $C_3 = 0.02186$ ;  $C_4 = 6.85 \times 10^{-4}$ ; and  $t_d$  = consolidation time (days). The squared correlation coefficient  $r^2$  is 0.3563, which is rather low because of the small sample size and range of reported entrainment rates. The constants  $C_2$ ,  $C_3$ , and  $C_4$  will have different values if other experimental data are used to find  $A_B$ , but we propose that Eq. 6 is a reasonable function. These data do not fit an exponential function as well as the consolidation data because of the complex impacts of biological processes. For example, Lintern *et al.* (2002) noted the presence of diatoms and other biological material within the homogenized sediment, in addition to complex structures caused by burrowing organisms. Furthermore, not all biological activity increases erodibility; for example, biofilms promote stability in sediments whereas bioturbation destabilizes the bed. Overall, these deposits were mostly bioturbated, which is the

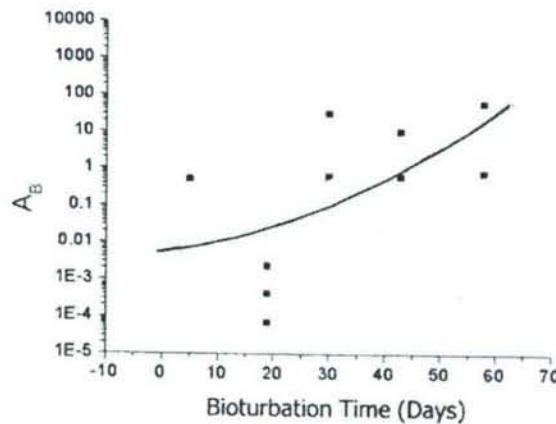


Fig. 2. Plot of the bioturbation coefficient  $A_B$  for the data from Table 2. The line is a plot of Eq. 6 ( $r^2 = 0.3563$ ). The coefficient  $A_B \equiv E_0/E_{M1}$  from Table 2. Note that the first data entry is not plotted. See text for explanation.

reason Fig. 2 shows a slight increase in entrainment with time. If the data used to calculate  $A_0$  are representative of newly deposited sediment,  $A_B$  should always be greater than unity because of the increasing disruption as organisms bioturbate the bed. However, as seen in Fig. 2,  $A_B$  is less than 1 for most bioturbation times because of the experimental uncertainty (note the 3 data points at 19 days).

#### 4.4. Comparison to other entrainment data

The sediment samples studied by Tsai and Lick (1988) were collected in a water depth of 20 m in Long Island Sound. They contained dark grey organic silt and clay with 95% finer than 74  $\mu\text{m}$ . The samples were homogenized and placed in an annular flume 0.204 m deep. The water content at the time of testing varied from 70.4 to 72.2%. This is a small range and, in fact, there was some overlap in water content during the consolidation interval. The value of  $\tau_c$  was not reported so we use 0.04 Pa. A comparison will be made with the first-hour resuspension rate (Fig. 4 from Tsai and Lick, 1988), so a time step of 3600 s is used. The value of  $A_0$  ( $1.523 \times 10^{-7} \text{ kg/m}^2/\text{s}$ ) was determined from samples that were measured after 1 day of consolidation as discussed above.

The entrainment data for these samples are given in Table 3. There is a significant trend of decreasing entrainment rate with time (correlated with water content) for the observations at all shear stresses (open squares in Fig. 3). This behavior is what we would expect for consolidation. Note that the consolidation interval labels (e.g., 1 D) on Fig. 3 refer to the measurements only. Equation 4 is solved using the base entrainment ( $A_B = A_C = 1$ ) and plotted on Fig. 3 as well (open circles,  $E_{M1}$  in Table 3). Note that the data points for all water contents fall upon each other, because of the lack of consolidation when  $A_C = 1$ . This is the reason it is necessary to adjust other parameters for Eqs. 1–3. The prediction is not bad because the total consolidation interval was only 7 days. The effects of consolidation are seen at all shear stresses when  $A_C$  is computed using Eq. 5, however. The results (crosses in Fig. 3) match the measurements better as well ( $E_{M2}$  in Table 3).

Some of the homogenized sediment from Long Island Sound was seeded with deposit-feeding *Nucula* clams at a density of 1150/m<sup>2</sup> (Tsai and Lick, 1988). This significantly increased the equilibrium concentration of sediment at all shear stresses. Tsai and Lick (1988) report the first-hour entrainment rate for the sterile data but only the mean concentration  $C_M$  at different shear stresses for the seeded samples. Nevertheless, the entrainment rate can be approximated from  $C_M$  by:  $E = h[C_M(t+\Delta t) - C_M(t)]/\Delta t$ , where  $h$  = the flume depth (0.204 m) and  $\Delta t$  = the time to reach  $C_M$  for an increase in  $\tau_b$ . This calculation was performed on the data of Tsai and Lick (their Fig. 8) for comparison with the values predicted by Eq. 4 using Eq. 6 to find the bioturbation coefficient  $A_B$ .



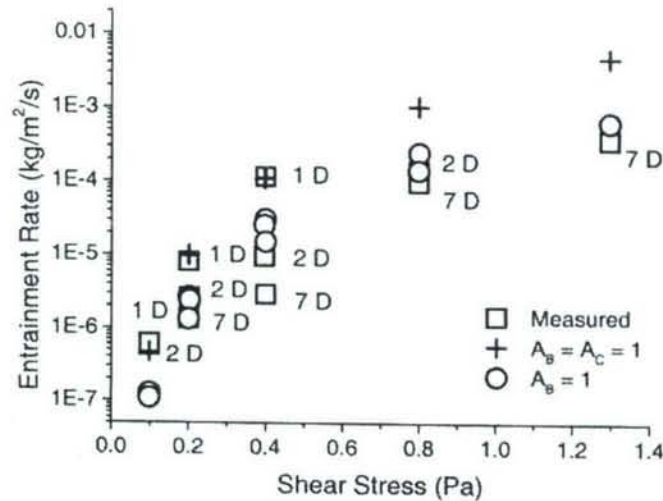


Fig. 3. Plot of the entrainment data for Long Island Sound sediment: measured ( $E_0$ ) (Tsai and Lick, 1988) (squares); calculated by Eq. 4 with  $A_B = A_C = 1$  ( $E_{M1}$ , pluses); and Eq. 4 with  $A_C$  calculated by Eq. 5 and  $A_C = 1$  ( $E_{M2}$ , circles). The consolidation intervals in days for the measured data are indicated.

The results (Fig. 4) show that Eq. 6 is not general enough for wide application because it was derived from a limited database with somewhat unique characteristics.

The entrainment rates for the undisturbed sediment from the Fox River were measured using SEDFLUME (McNeil *et al.*, 1996). This sediment contained silt and clay (mean grain size less than 20  $\mu\text{m}$ ), gas bubbles, infauna, grass, and organic carbon (approximately 10%). The entrainment rate was measured at a range of depths within the core for shear stresses ranging from 0.25 – 4.5 Pa. The water content varied from 64.8% at the surface to 48.1% at depth, indicating that this sediment was not freshly deposited. A base entrainment rate ( $A_0$ ) of  $2.259 \times 10^{-2} \text{ kg/m}^2/\text{s}$ , is calculated as described in section 4.1 and  $A_C$  is computed using Eq. 5. The bulk density required to calculate  $E$  is found using bulk density data from McNeil *et al.* (1996, Fig. 8); the surface bulk density of the core was  $1166 \text{ kg/m}^3$ . The entrainment rates for the measured samples (squares in Fig. 5) vary at smaller values of  $\tau_b$  and increase with shear stress. The entrainment rates predicted by Eq. 4 increase with shear stress also while being an order-of-magnitude high at large shear stresses. The predicted entrainment rates are

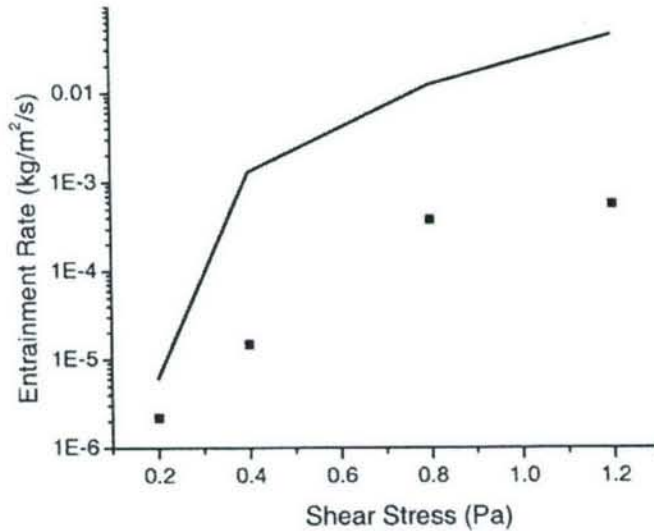


Fig. 4. Plot of the entrainment data for Long Island Sound sediment seeded with *Nucula* after 7 days (Tsai and Lick, 1988). The following conditions were used for the simulation: time step = 3600 s;  $\tau_c = 0.04$  Pa;  $A_B$  calculated from Eq. 6;  $A_C = 1$ ;  $A_0 = 1.523 \times 10^{-7}$  kg/m<sup>2</sup>/s.

probably too high because of post-depositional modification of the sediment. The consolidation expression (Eq. 5) is based on limited data from deposited slurries. Despite the difficulties of predicting the behavior of this sediment, the fit is reasonable, especially since no curve-fitting process was used for consolidation. It should also be noted that the base entrainment coefficient for this sediment, which was estimated from a surface sample, probably does not incorporate the effects of burial as deep as 0.4 m.

## 5. CONCLUSIONS

Consolidation and bioturbation appear to have opposing effects on cohesive sediment entrainment for most of the sediment studied herein. For example, bioturbation by infauna reworks sediment and increases erodibility for these samples whereas consolidation and dewatering tends to decrease entrainment rates. Thus, these preliminary results

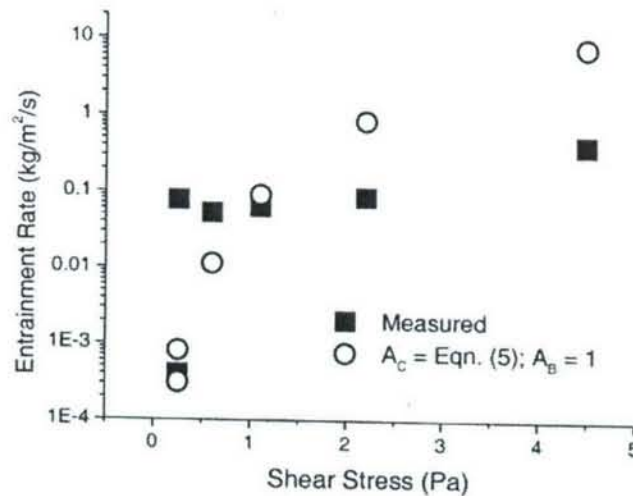


Fig. 5. Entrainment rates for Fox River sediments (McNeil *et al.*, 1996). The following conditions were used for the simulation: time step = 3600 s;  $\tau_c = 0.1$  Pa;  $A_C$  calculated from Eq. 5;  $A_B = 1$ ;  $A_0 = 2.259 \times 10^{-2}$  kg/m<sup>2</sup>/s.

suggest that, as a first approximation, these processes can be treated as mutually exclusive. If bioturbation is significant, consolidation can probably be neglected and  $A_C$  assumed to be 1, whereas if bioturbation is negligible (*i.e.*, rapid deposition and/or a hypoxic water column), the sediment's physical properties are probably dominated by consolidation or other processes that decrease erodibility (*e.g.*, organic content). It is not suggested that this simple approach incorporates all environmental effects but it is usable until better entrainment data become available. The greatest advantage of the modular entrainment model (Eq. 4) is that it permits us to examine this complex process with a more physically realistic approach than parameter calibration based on entrainment data.



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